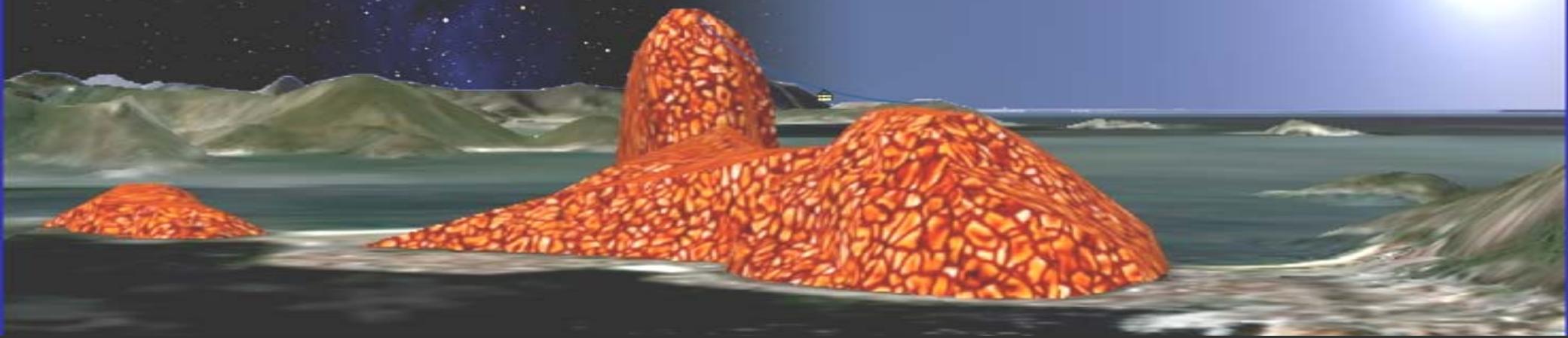


# 3D Views on Cool Stellar Atmospheres

Theory meets observation



## Highest-Resolution Spectroscopy at the Largest Telescopes ?

*Dainis Dravins* – Lund Observatory, Sweden

[www.astro.lu.se/~dainis](http://www.astro.lu.se/~dainis)



But why?

Changing paradigms...

PHYSIK DER  
STERNATMOSPHÄREN

MIT BESONDERER BERÜCKSICHTIGUNG DER SONNE

VON

DR. A. UNSÖLD

PROFESSOR FÜR THEORETISCHE PHYSIK  
AN DER UNIVERSITÄT KIEL

MIT 145 FIGUREN IM TEXT



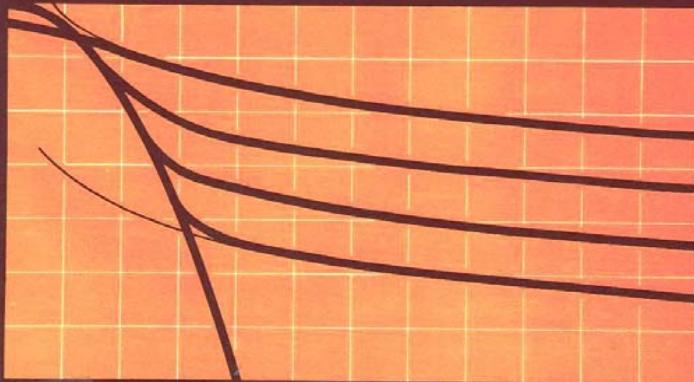
BERLIN

VERLAG VON JULIUS SPRINGER

1938

A.Unsöld  
Physik  
der Stern-  
atmosphären

Zweite Auflage

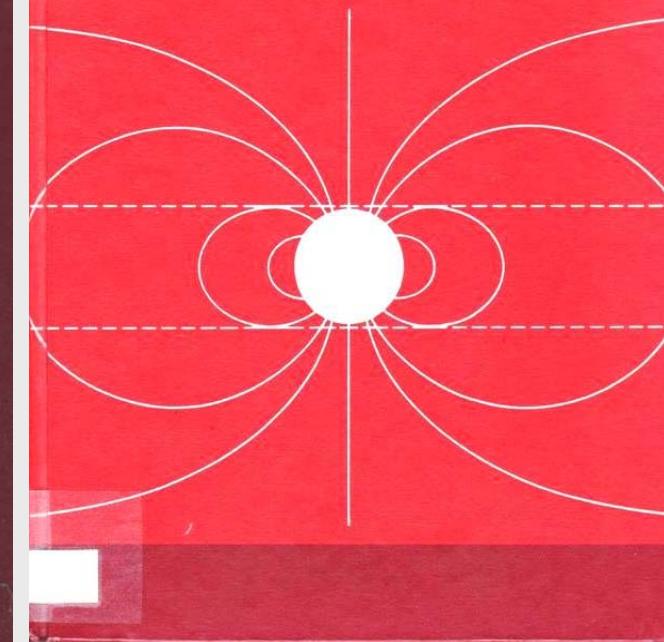


Springer - Verlag  
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STELLAR  
ATMOSPHERES

SECOND EDITION

MIHALAS

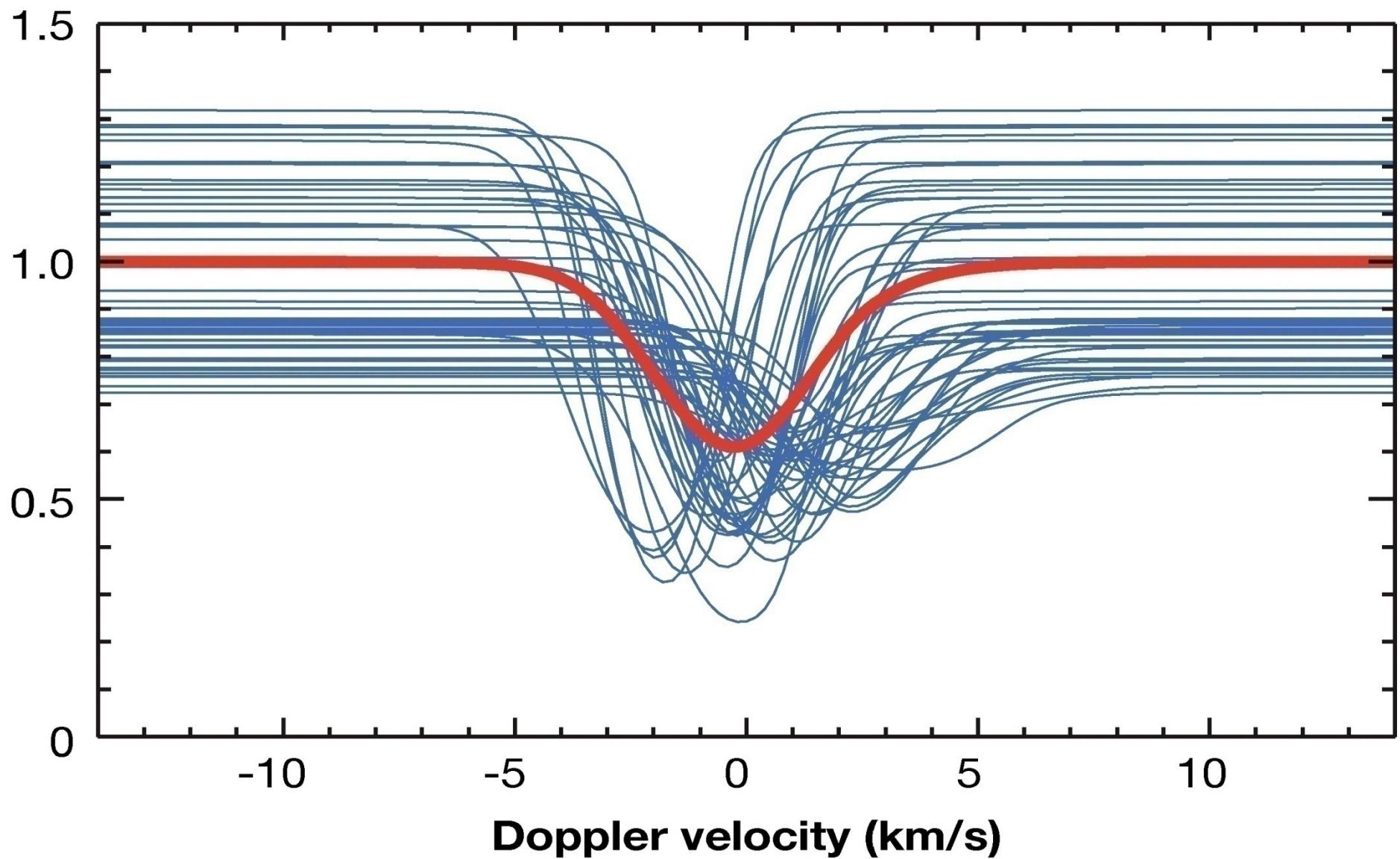


Stellar atmosphere theory classics...  
Unsöld (1938, 1968); Mihalas (1969, 1978)

# *CHANGING STELLAR PARADIGMS*

- **PAST:** "Inversion" of line profiles; "*any part of a profile corresponds to some height of formation*"
- **NOW:** Stellar line profiles reflect distribution of lateral inhomogeneities across stellar surfaces
- Not possible, *not even in principle*, to "invert" observed profiles into atmospheric parameters
- Confrontation with theory through "forward modeling" – computations versus observables

**Relative intensity**



Spatially resolved line profiles of the Fe I 608.27 nm line in a 3-D solar simulation.

Thick red line is the spatially averaged profile.

Steeper temperature gradients in upflows tend to make their blue-shifted lines stronger

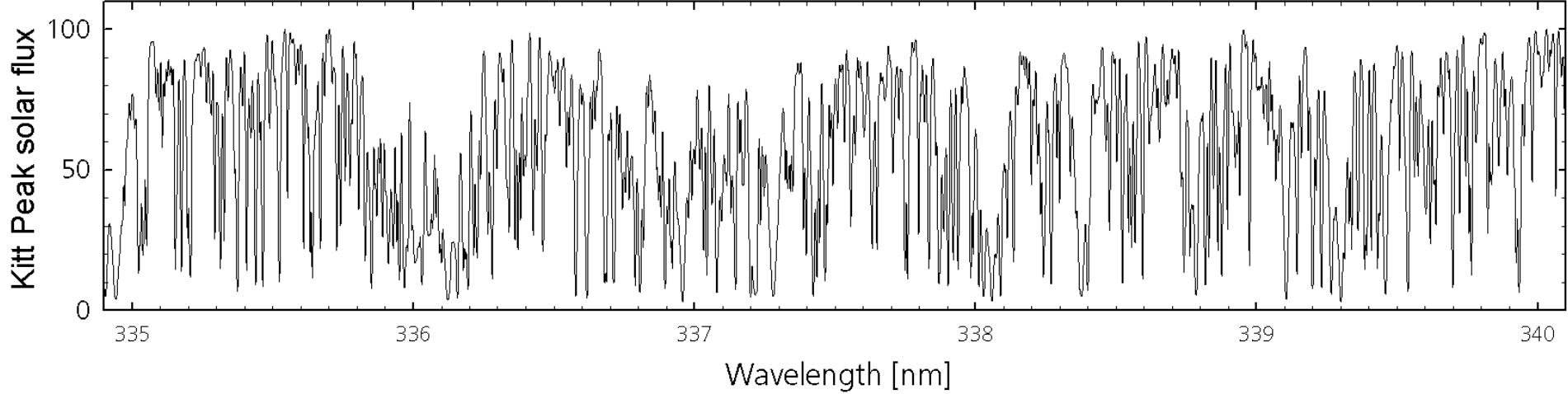
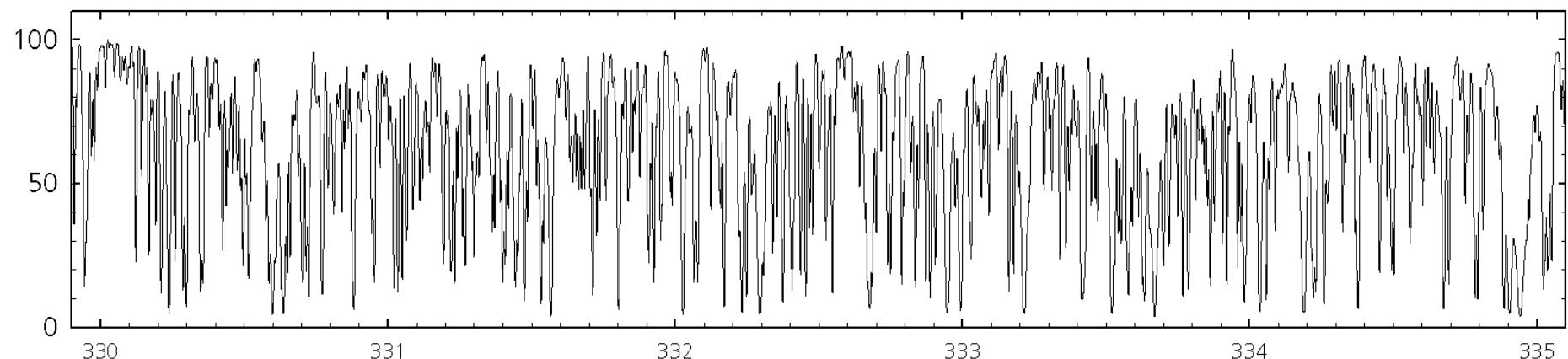
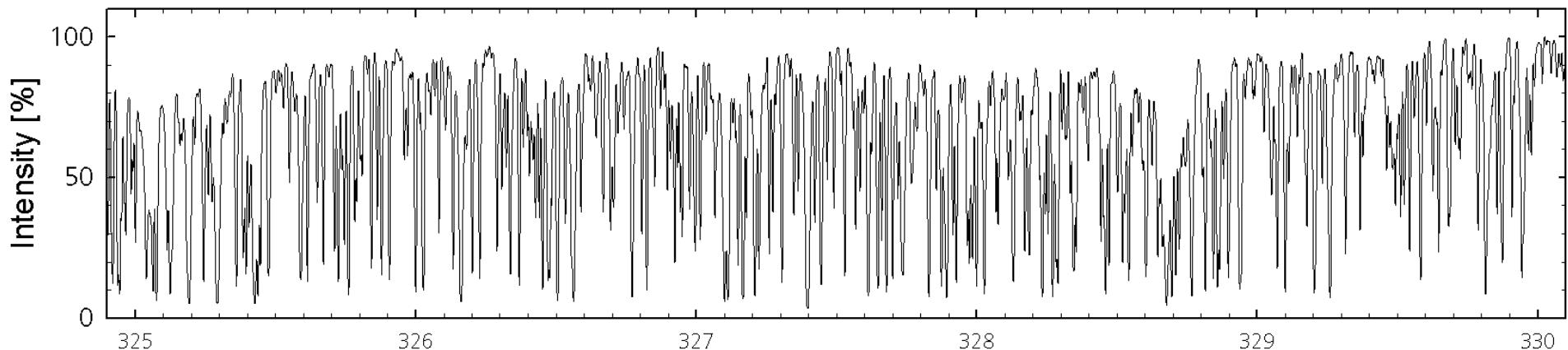
Limits to  
information content  
of stellar spectra?

# "ULTIMATE" INFORMATION CONTENT OF STELLAR SPECTRA ?

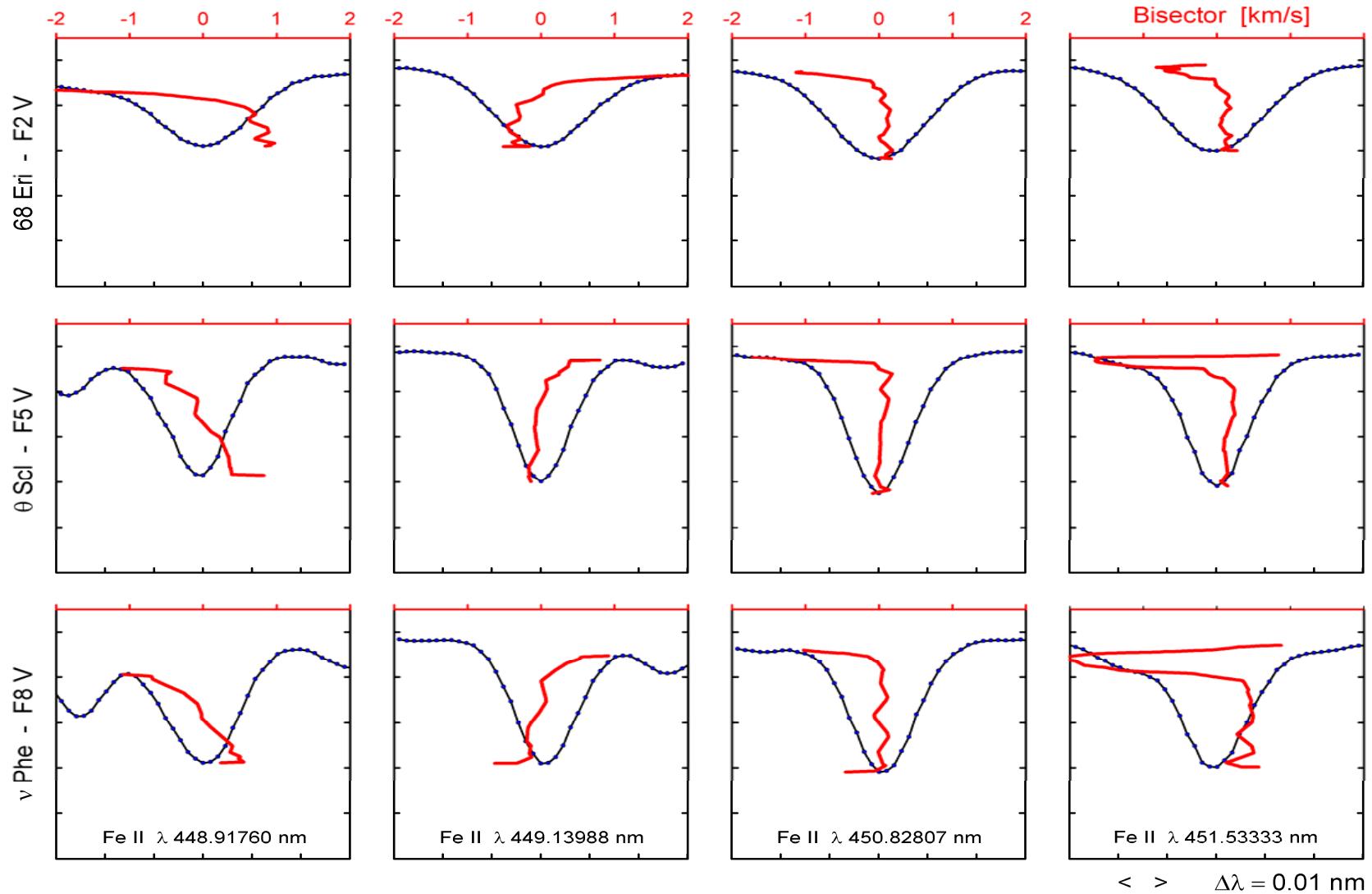
*3-D models predict detailed line shapes and shifts  
... but ...  
their predictions may not be verifiable due to:*

-  Absence of relevant stellar lines
-  Blends with stellar or telluric lines
-  Uncertain laboratory wavelengths
-  Data noisy, low resolution, poor wavelengths
-  Line-broadening: rotation, oscillations

# Spectral complexity

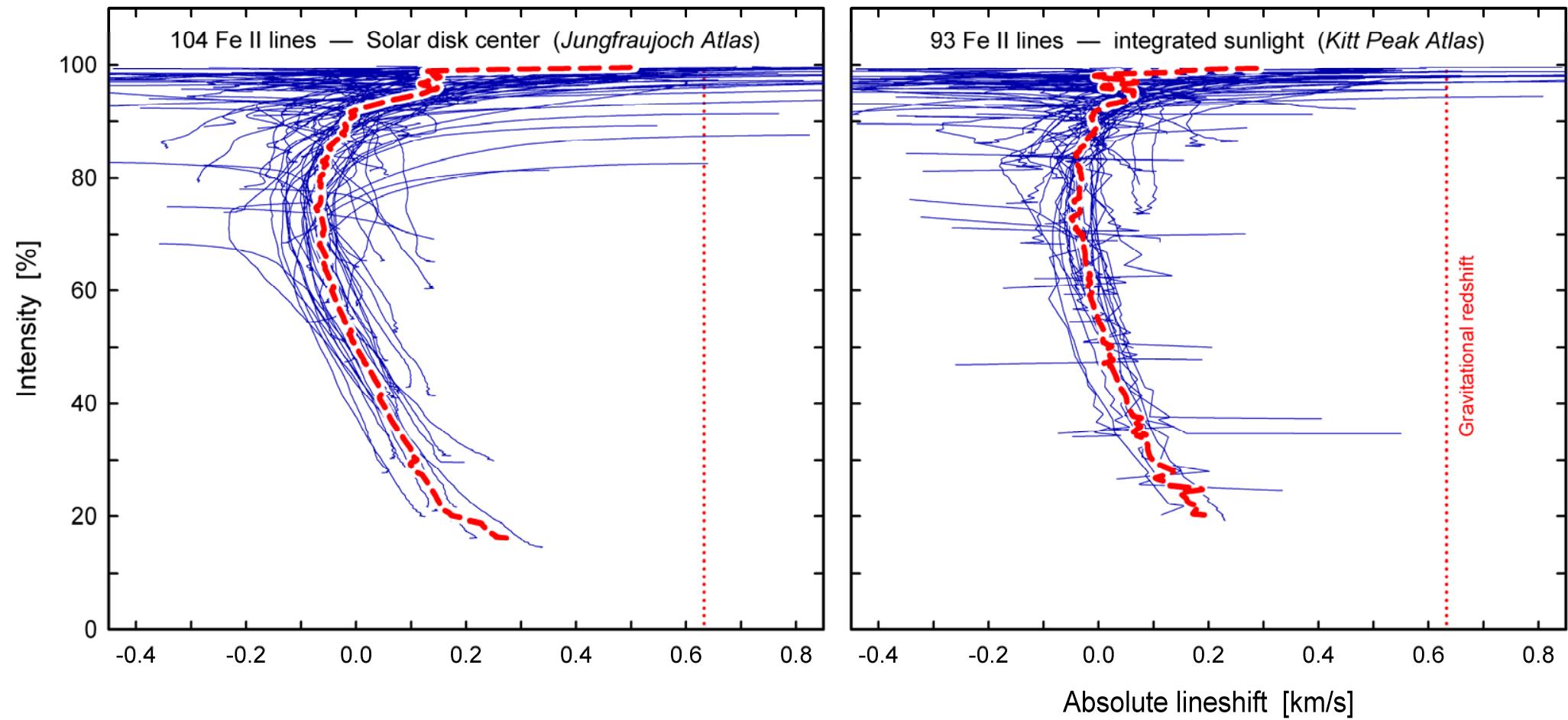


# Limits of 'unblended' lines ?



Individual bisectors (red), overplotted on line profiles, for Fe II lines in UVES Paranal spectra of 68 Eri (F2 V), θ Scl (F5 V), and ν Phe (F9 V). Bisector scale (top) is expanded a factor of 10. Dravins, A&A 492, 199 (2008)

# Limits to line statistics ?

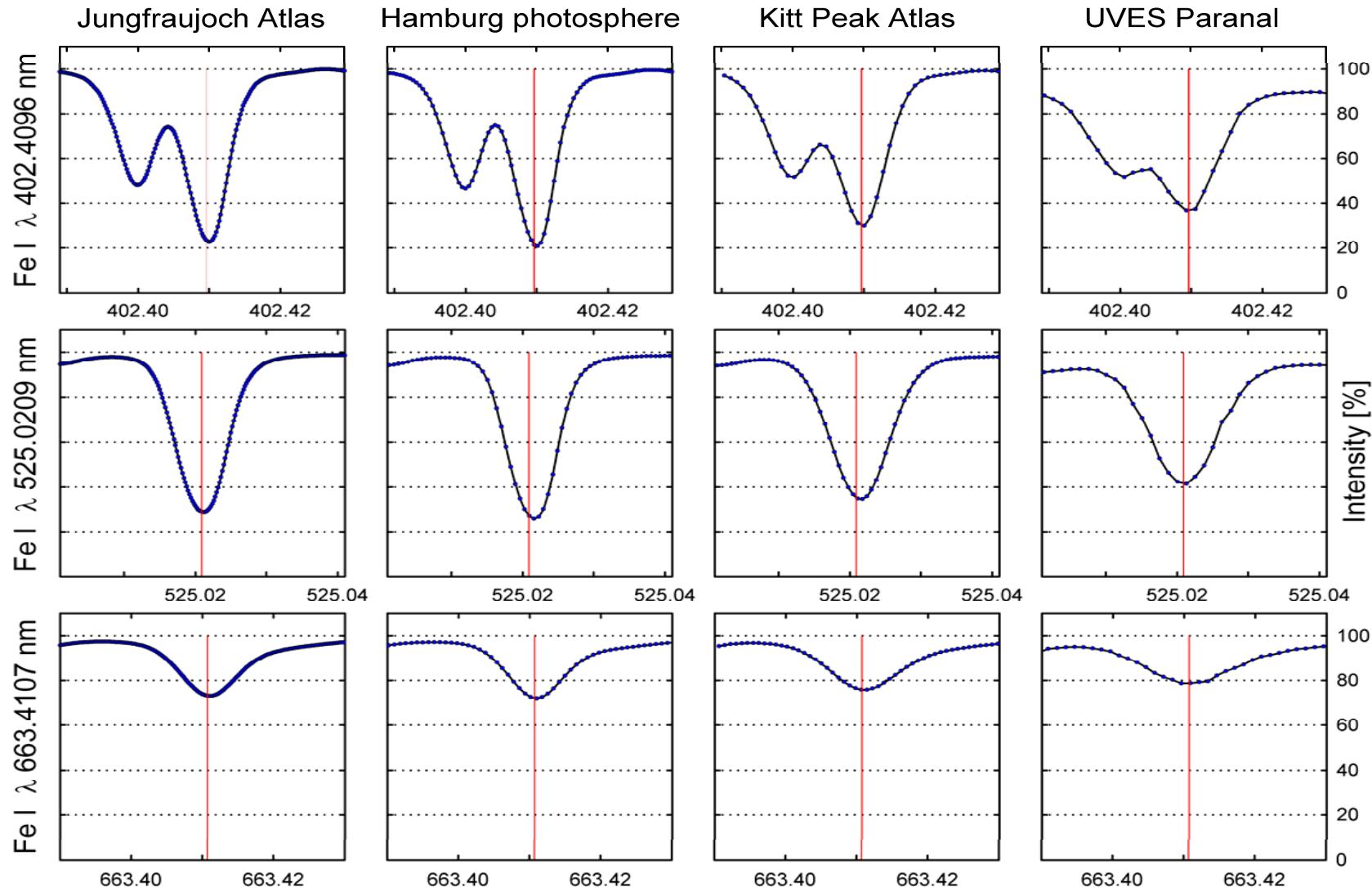


Fe II bisectors at solar disk center, and of integrated sunlight, on an absolute wavelength scale. Thin curves are individual bisectors; thick dashed is their average.

Dravins, A&A 492, 199 (2008)

# Finite spectral resolution

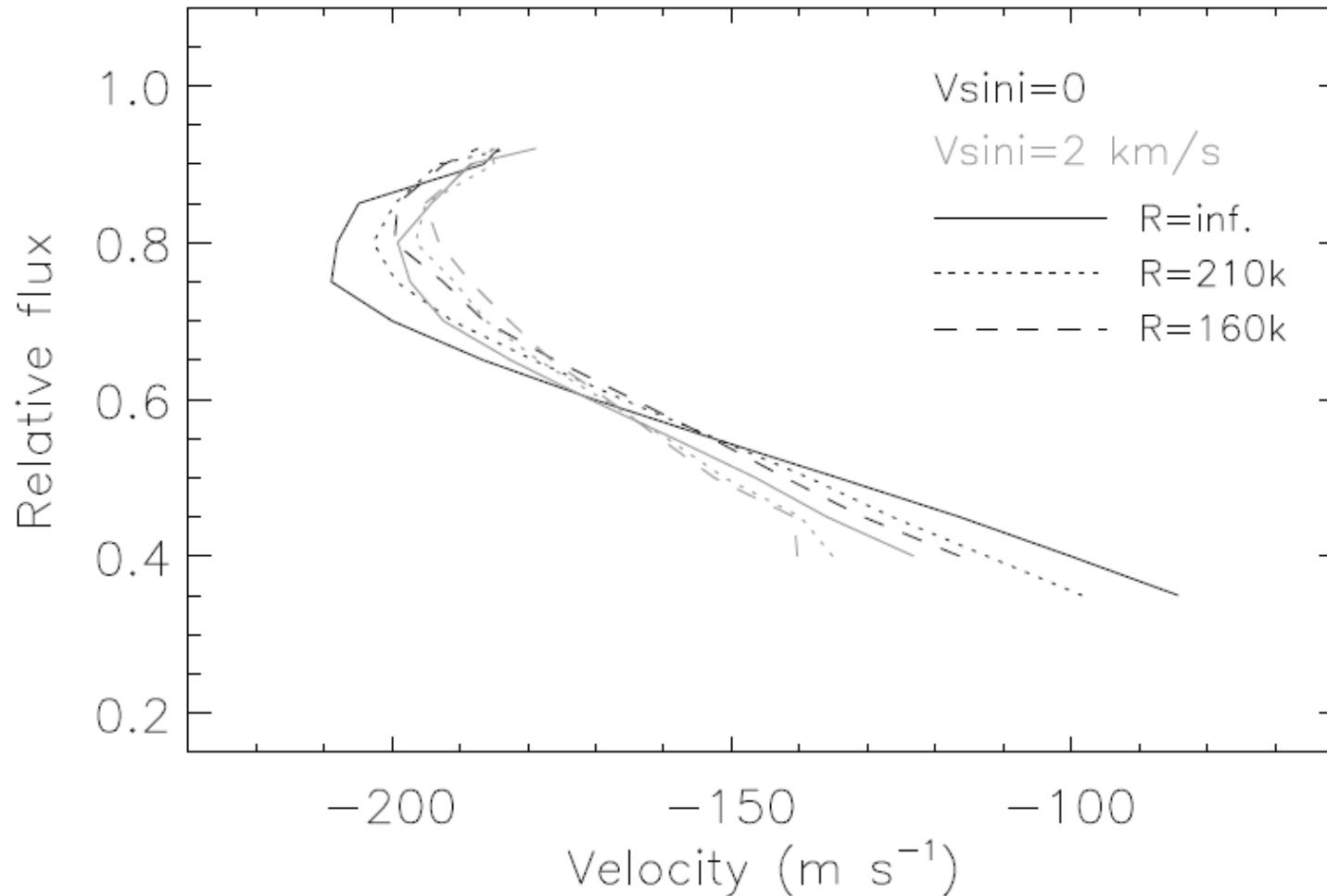
# Limits to spectral fidelity ?



Different line profiles in different recordings of solar spectra.

Solar disk center (Jungfraujoch & Hamburg); Integrated sunlight (Kitt Peak); Moonlight (UVES).  
Dravins, A&A 492, 199 (2008)

# Theoretical bisectors in K-type dwarfs, “observed” at R=160,000 & R=200,000



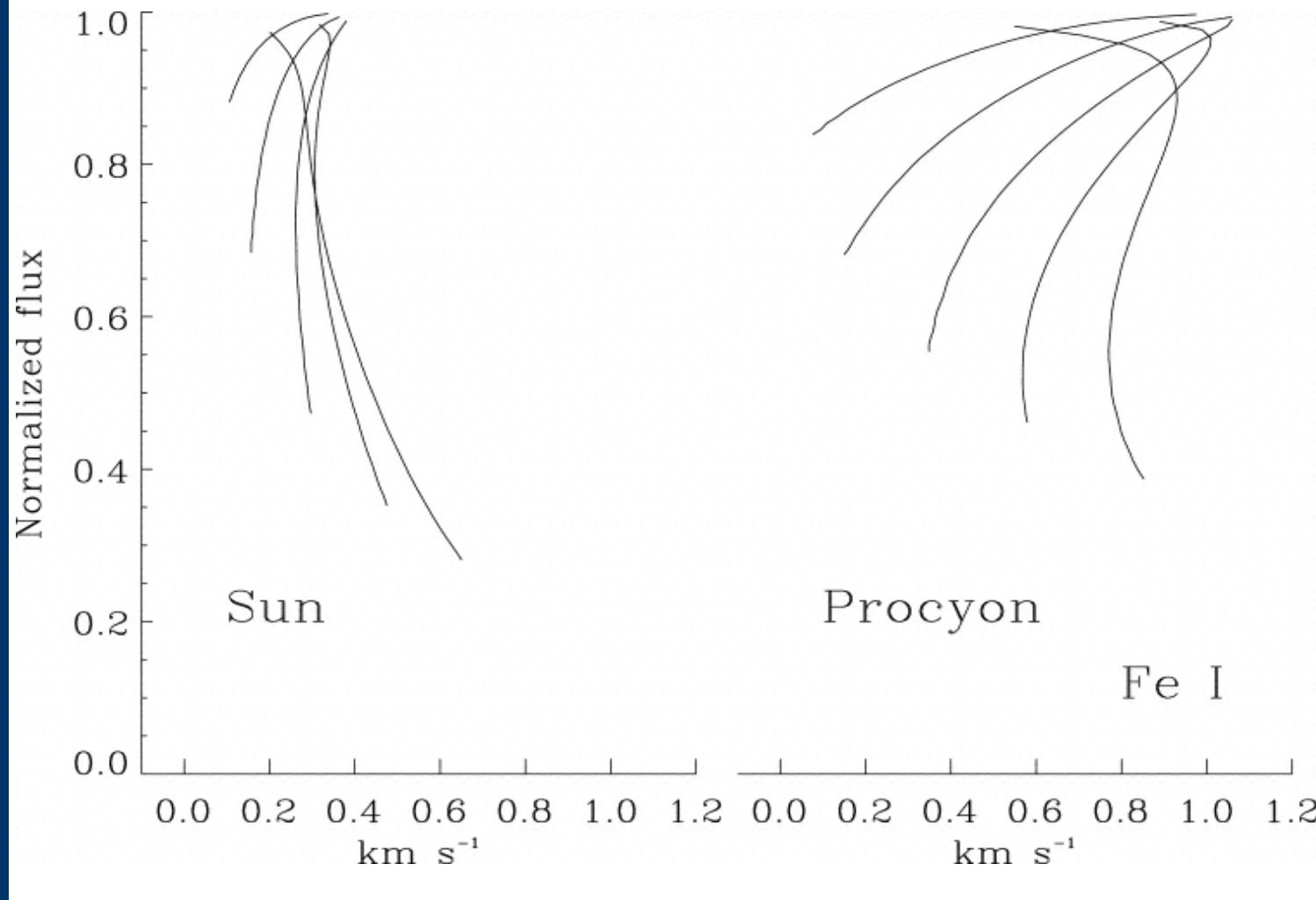
**Theoretical bisectors of 522.84 nm Fe I line for  $V \sin i = 0$  and 2 km/s, at  $R = \infty$ ,  $R = 210,000$ , and  $R = 160,000$**

I.Ramírez, C. Allende Prieto, L. Koesterke, D. L. Lambert, M. Asplund

*Granulation in K-type dwarf stars. II. Hydrodynamic simulations and 3D spectrum synthesis*

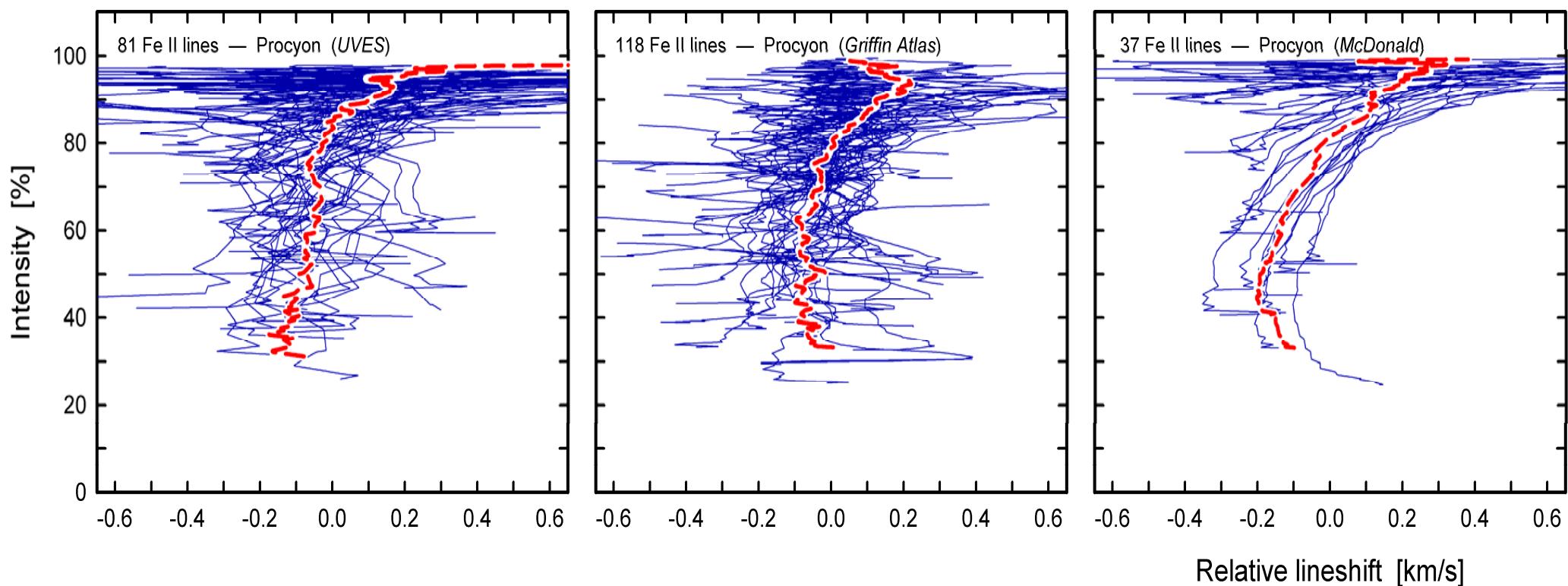
Astron. Astrophys. **501**, 1087 (2009)

# Fe I-line bisectors in Sun and Procyon (F5 IV-V)



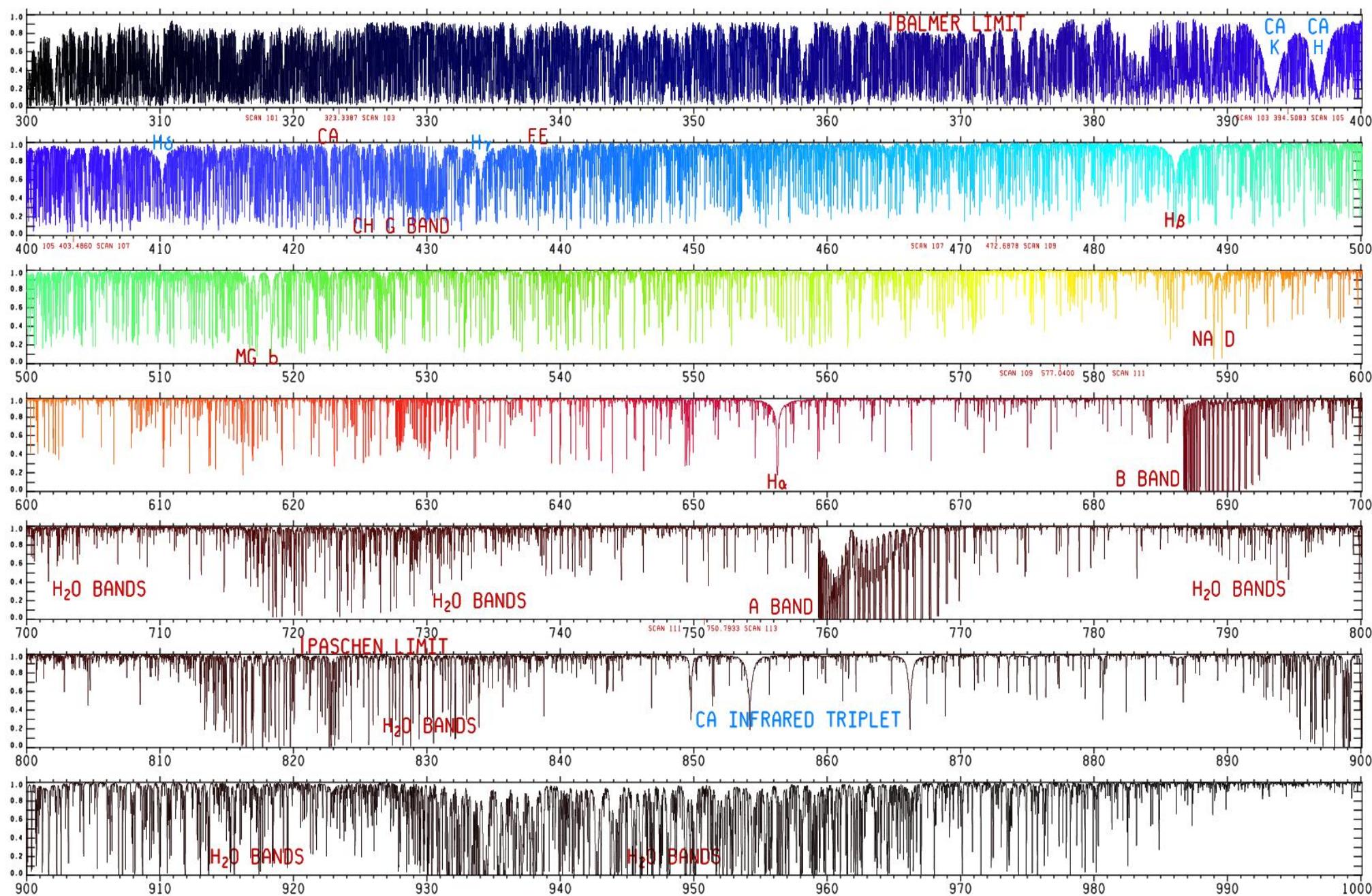
**Bisectors for Fe I lines of different strength,  
produced from a time-dependent 3-D model**

# Limits to spectral resolution ?



Fe II bisectors in Procyon, measured with successively higher spectral resolution.  
Left:  $R = 80,000$ ; Middle:  $R = 160,000$ ; Right:  $R = 200,000$ .  
Dravins, A&A 492, 199 (2008)

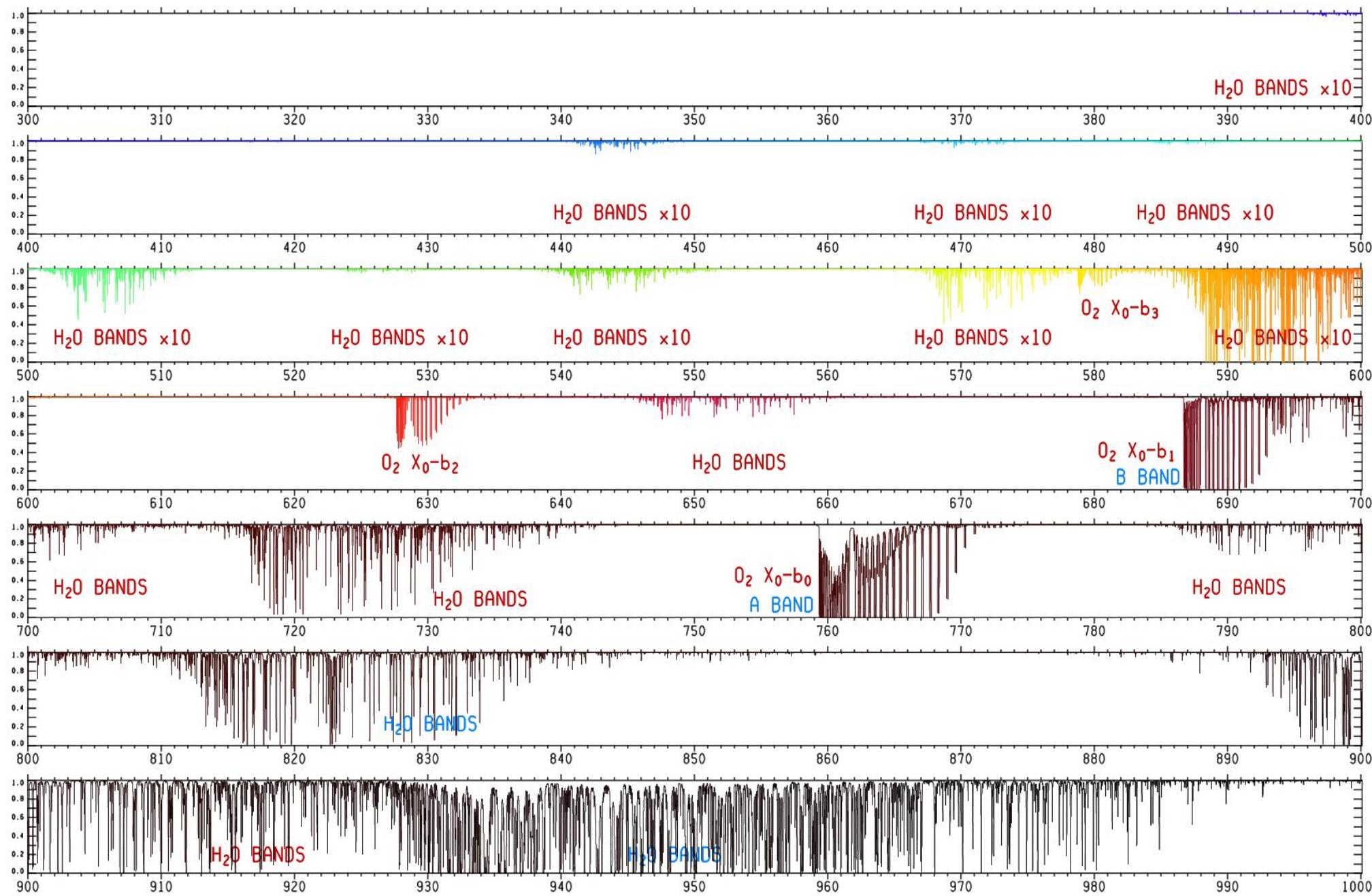
# Absorption in the Earth's atmosphere



## TELLURIC LINES IN KITT PEAK SOLAR FLUX ATLAS

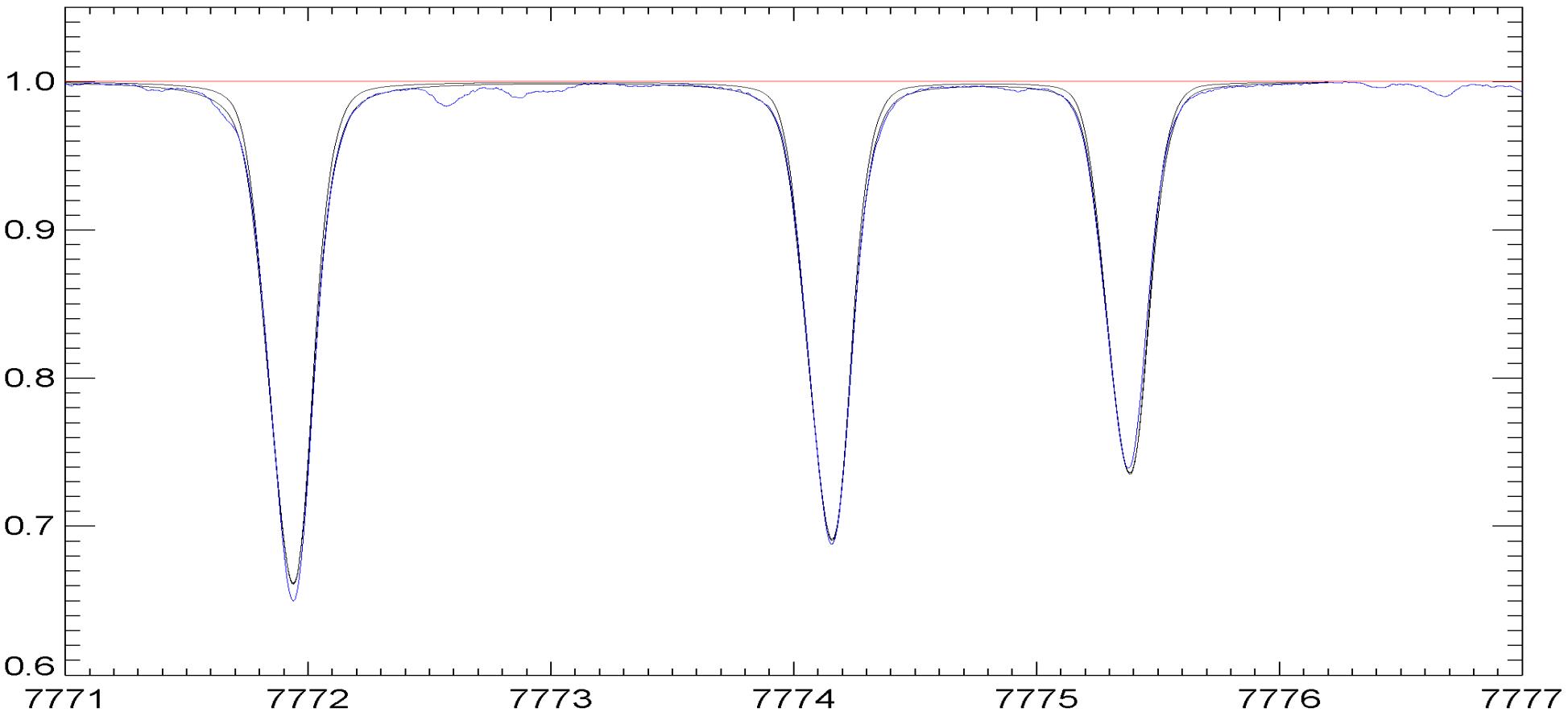
(KURUCZ 2005)

AIR WAVELENGTHS IN NM



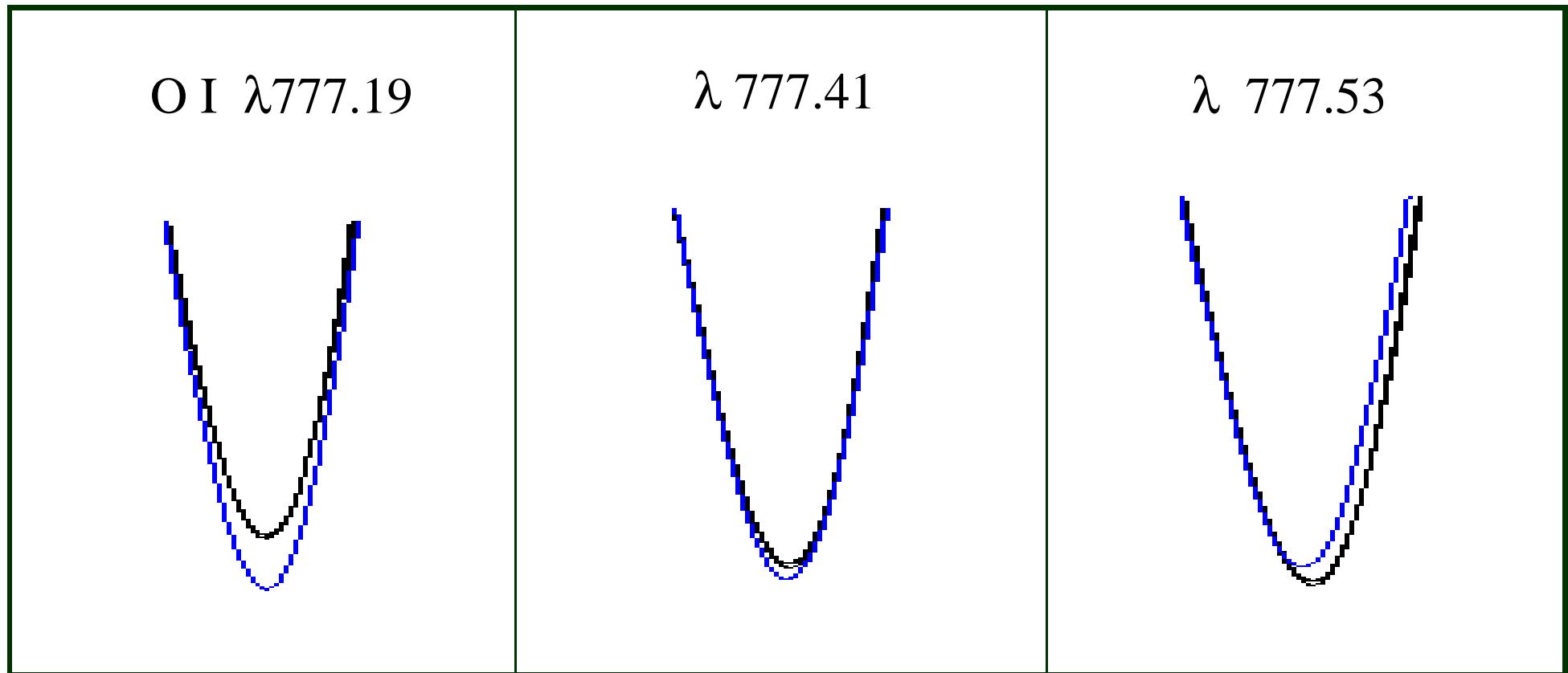
# Wavelength noise

# *MODELING SPECTRA (not only single lines)*



LTE solar 3-D spectra, assuming  $[O]=8.86$  for two different van der Waals damping constant (black lines).  
Blue line: observed disk center FTS spectrum by Neckel ("Hamburg photosphere"), slightly blueshifted.

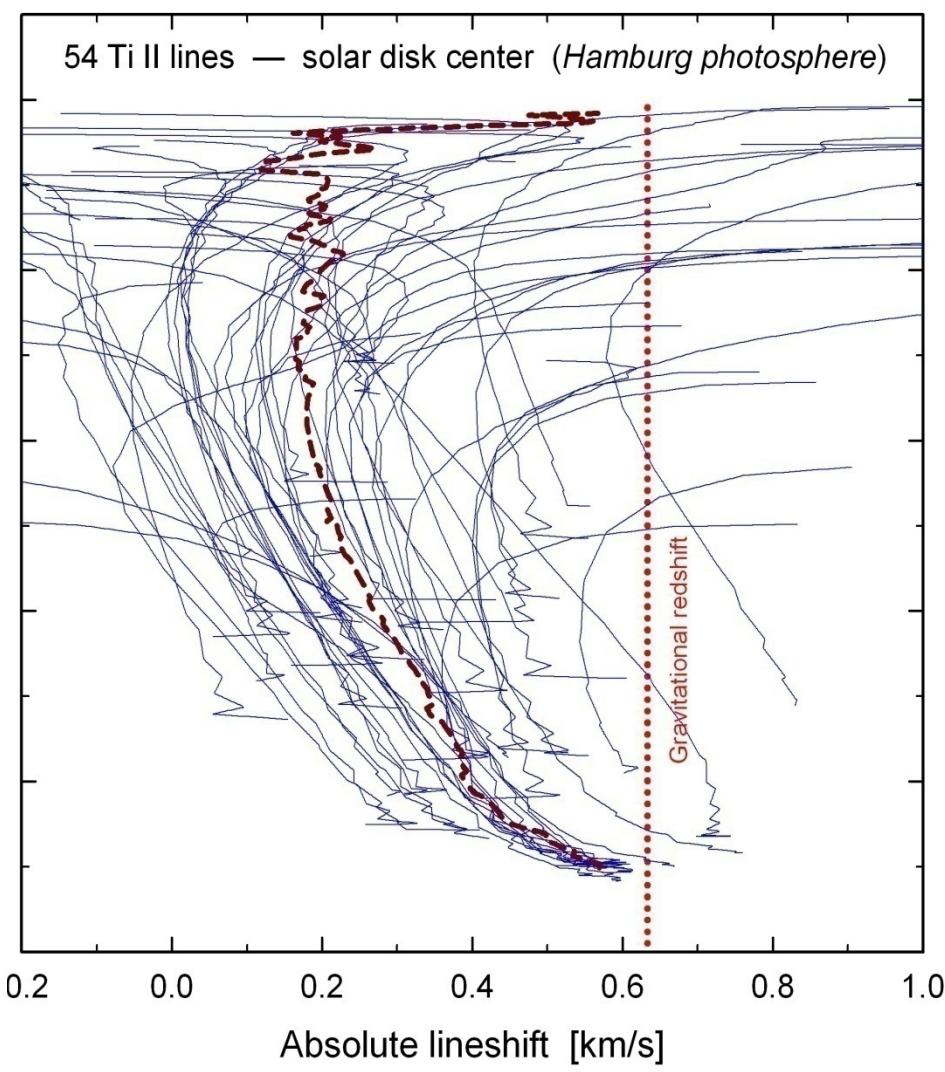
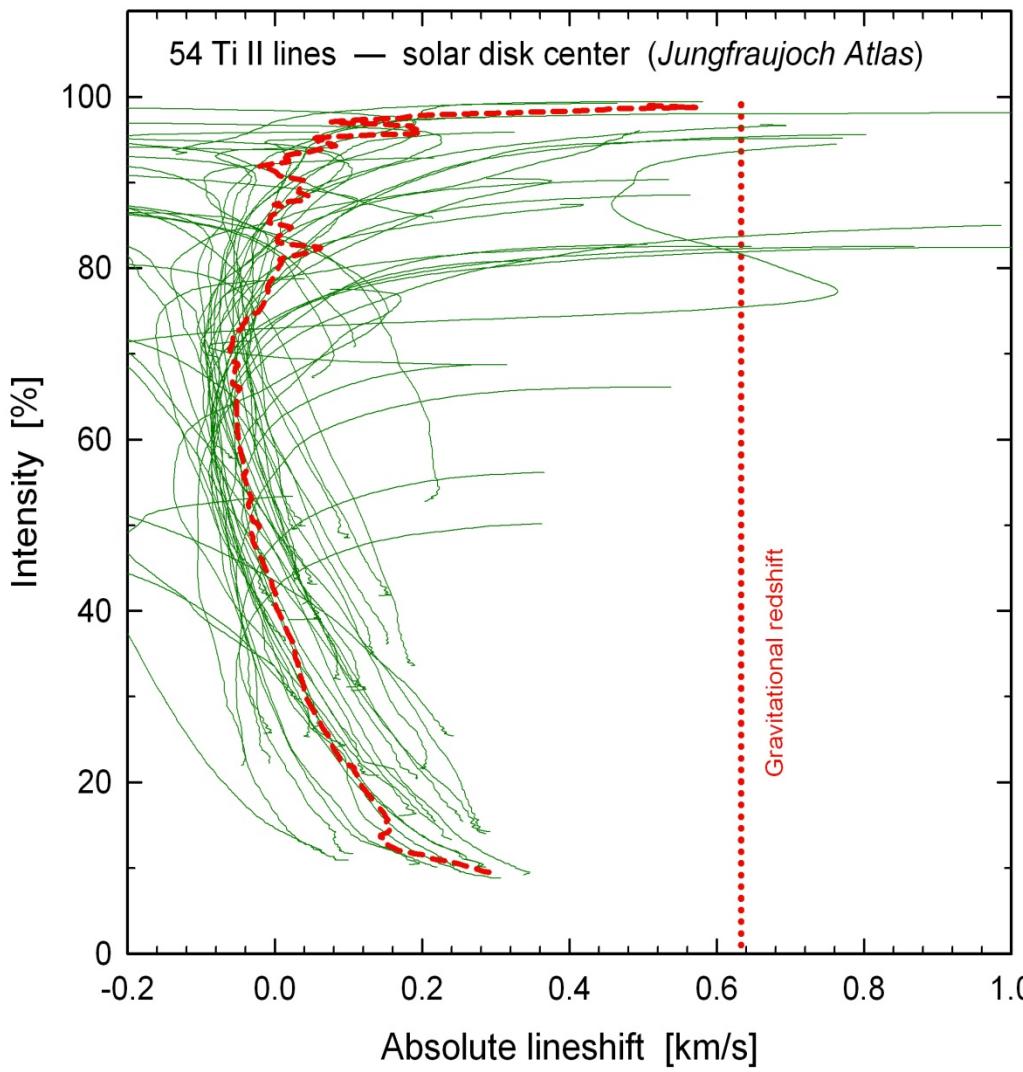
# O I LINE PROFILES & SHIFTS



LTE solar 3-D hydrodynamic spectra, assuming [O]=8.86, for two different damping constants (black lines).

Blue line: observed disk-center FTS spectrum, slightly blueshifted.

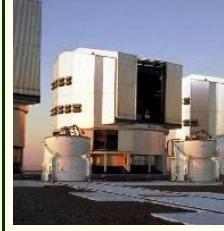
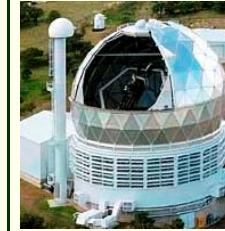
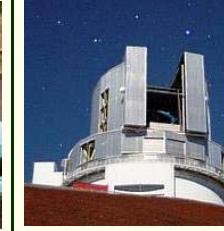
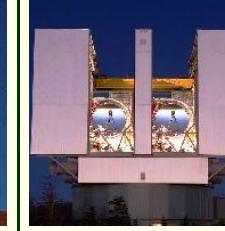
# Limits from wavelength noise ?

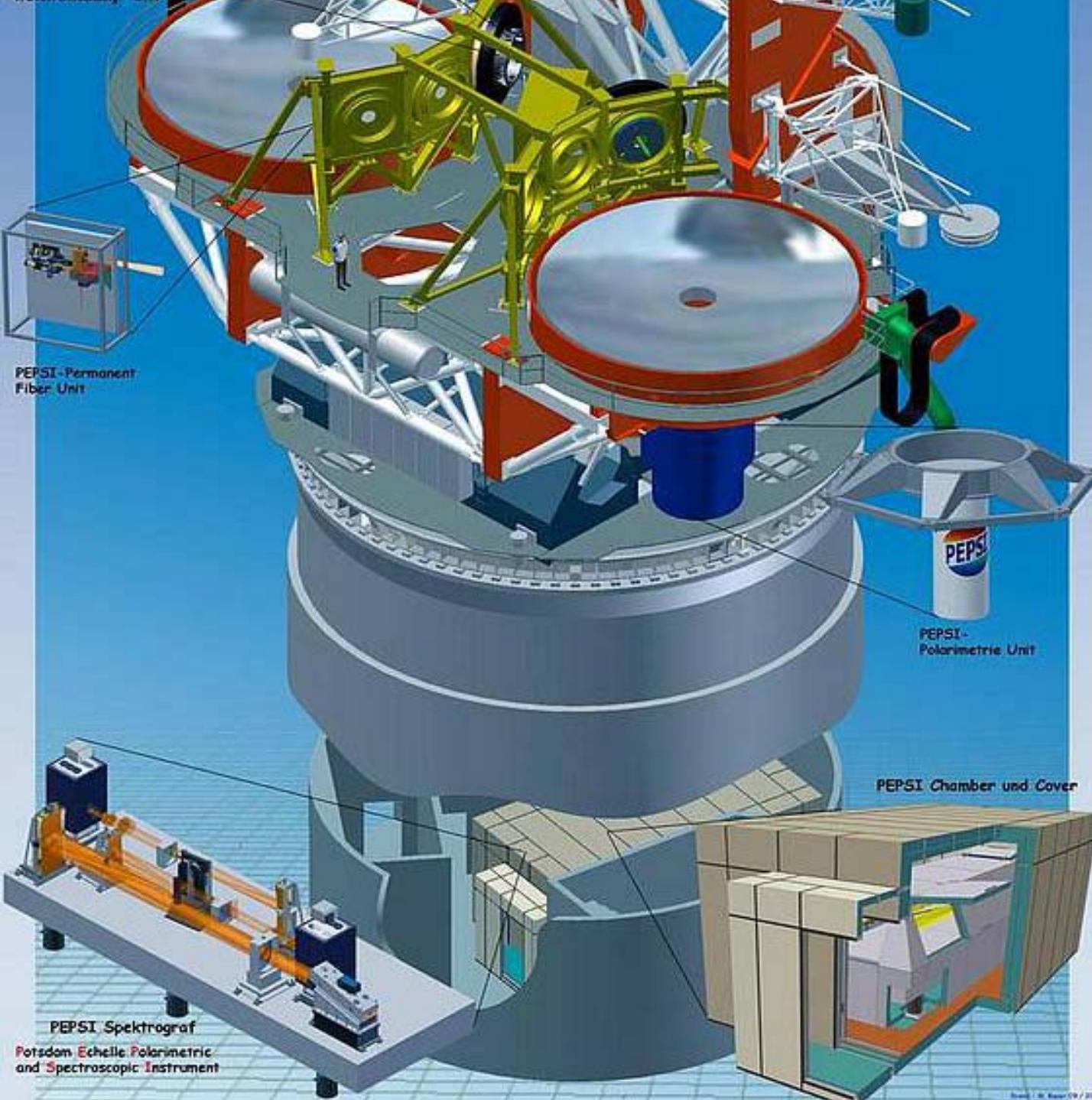


Ti II bisectors at solar disk center from the Jungfraujoch grating spectrometer, and as recorded with the Kitt Peak FTS . Bisectors have similar shapes but differ in average lineshift, and scatter about their average. Dravins, A&A 492, 199 (2008)

# Spectroscopy at Very & Extremely Large Telescopes

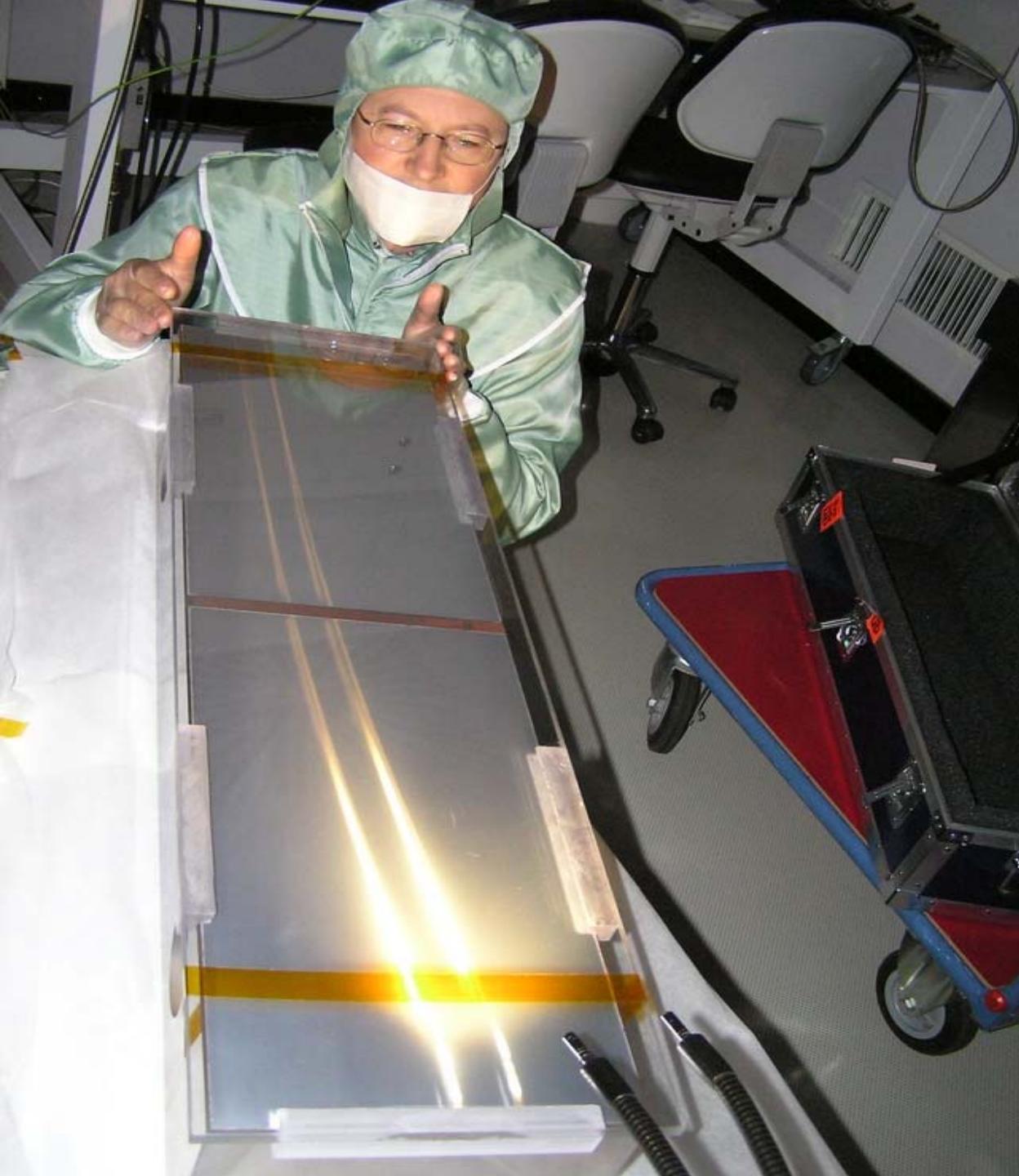
# Visual high-resolution spectrometers at 8-10 m telescopes

Telescope	SALT	Keck I	VLT Kueyen	HET	Subaru	LBT
						
Diameter [m]	10	10	8.2	9.2	8.2	$2 \times 8.4$
Spectrometer	<b>HRS</b>	<b>HIRES</b>	<b>UVES</b>	<b>HRS</b>	<b>HDS</b>	<b>PEPSI</b>
Maximum R	65,000	84,000	110,000	120,000	160,000	300,000
Wavelengths [ $\mu\text{m}$ ]	0.37– 0.89	0.3 – 1.0	0.3 – 1.1	0.39 – 1.1	0.3 – 1.0	0.39 – 1.05



*Potsdam  
Echelle  
Polarimetric  
and  
Spectroscopic  
Instrument  
@  
Large  
Binocular  
Telescope*

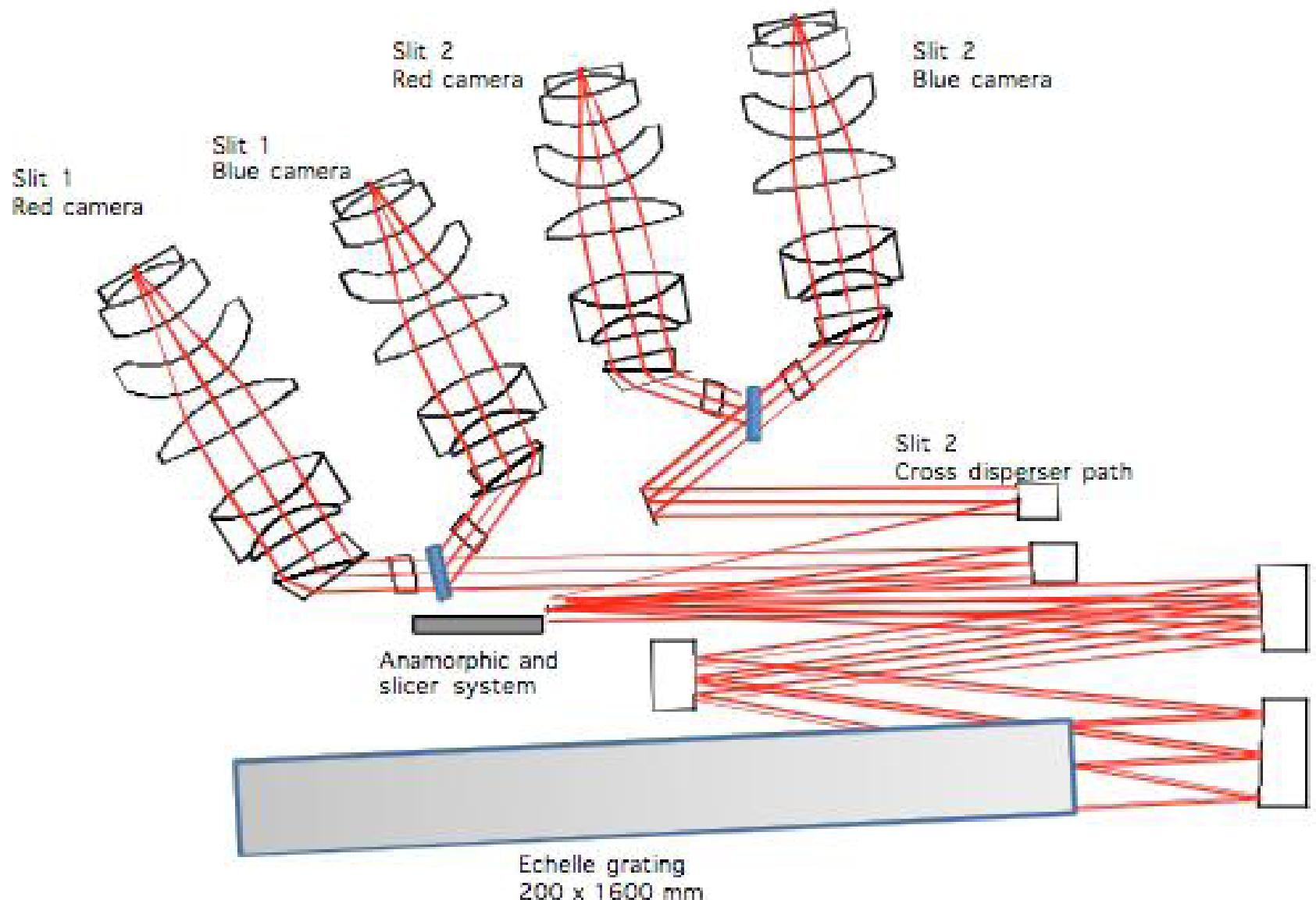


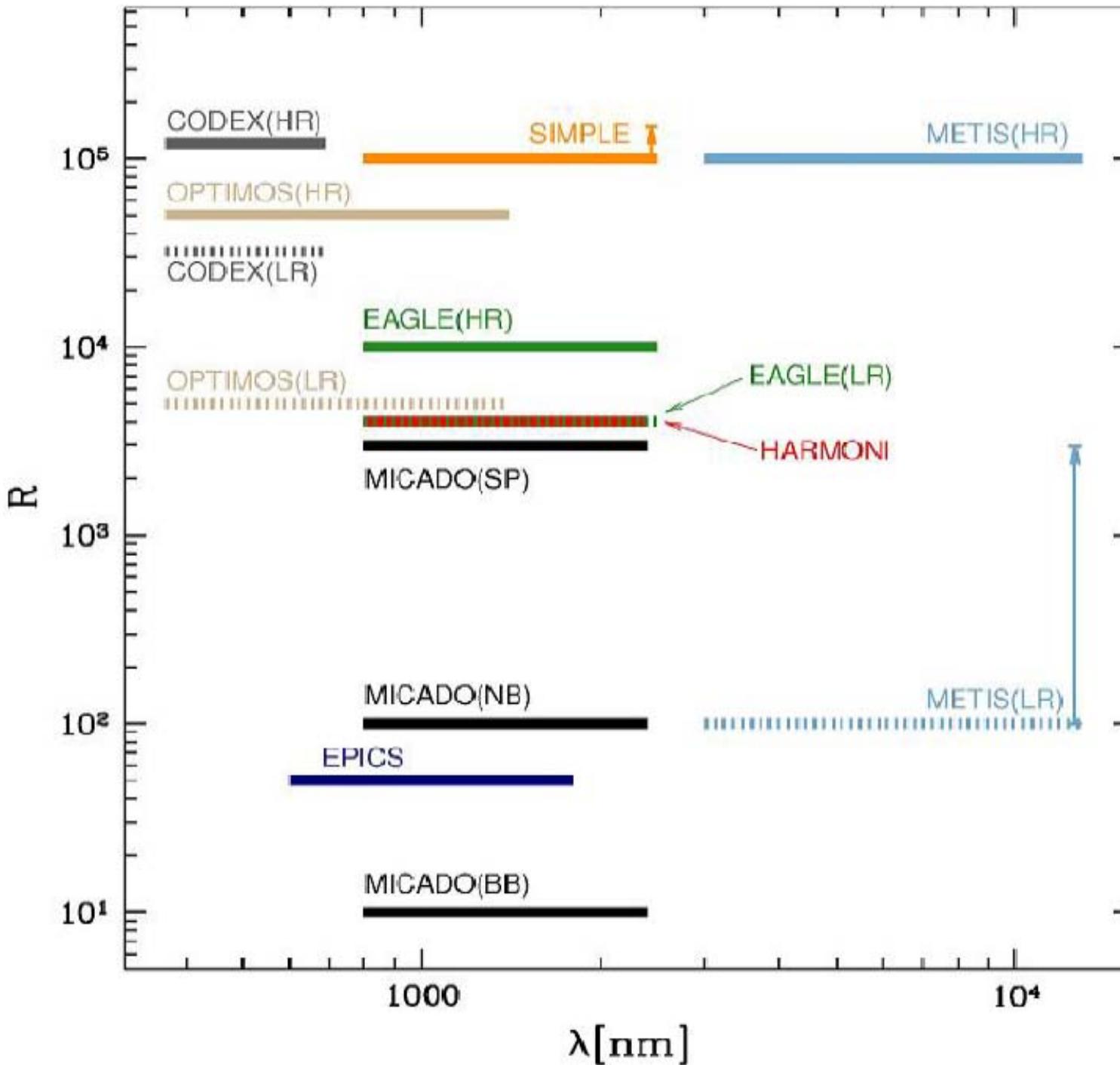


20x80 cm  
R4 echelle  
grating for  
PEPSI



# Optical arrangement of multi-camera CODEX design



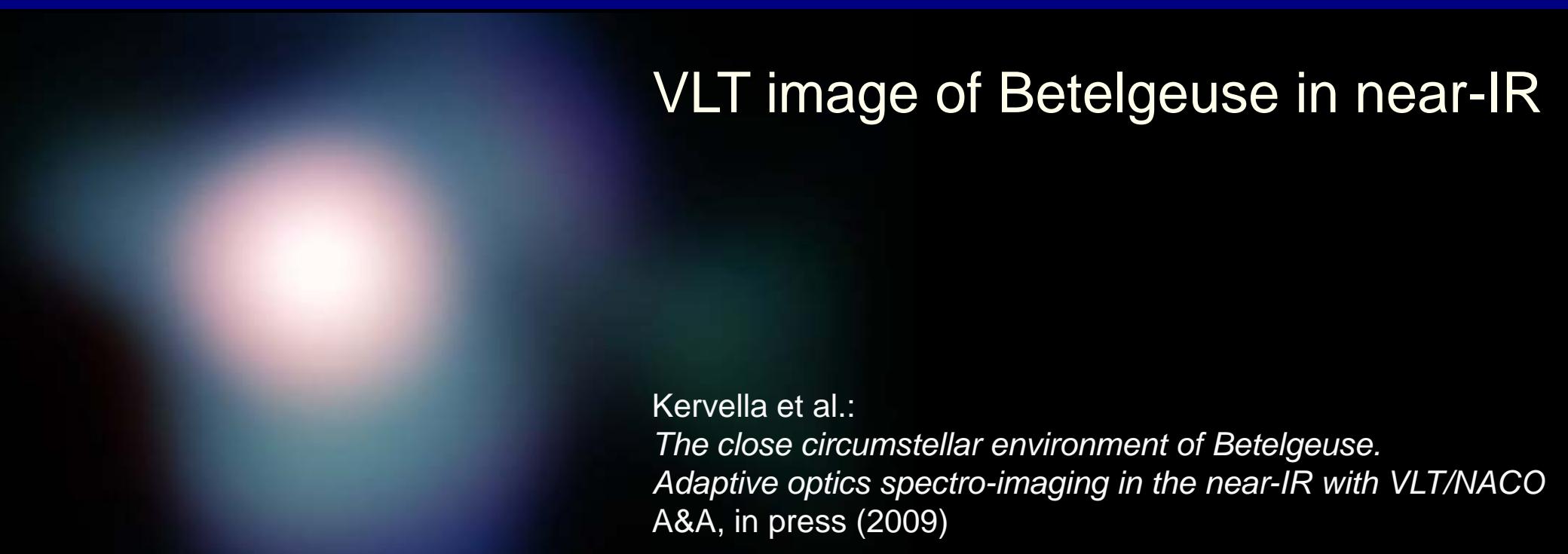


Resolving power and spectral range of proposed 42-m E-ELT spectrographs



# Beyond CODEX: Spatially resolved stellar spectroscopy

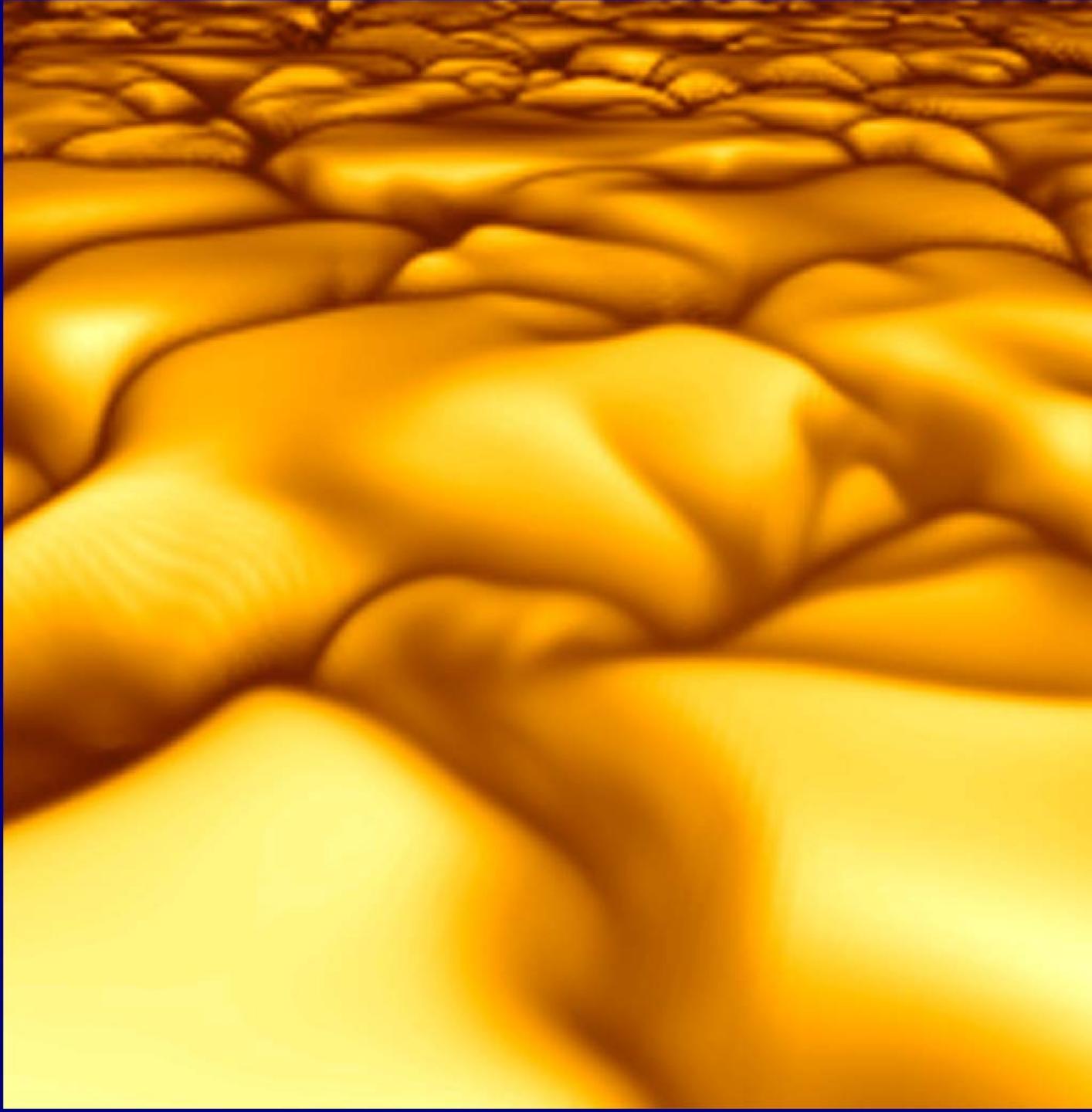
VLT image of Betelgeuse in near-IR



Kervella et al.:

*The close circumstellar environment of Betelgeuse.  
Adaptive optics spectro-imaging in the near-IR with VLT/NACO*  
A&A, in press (2009)

Corrugated  
stellar surfaces?

A detailed simulation of solar granulation, showing numerous small, roughly circular convective cells on the Sun's surface. The cells vary in size and intensity, creating a textured appearance. The colors range from deep orange and yellow in the centers to darker shades of yellow and white at the periphery of each granule.

# Simulated intensities approaching the solar limb

Mats Carlsson, Oslo;  
in  
Å.Nordlund, R.F.Stein,  
M.Asplund:  
*Solar Surface Convection,*  
*Living Reviews in Solar*  
*Physics, 2009*

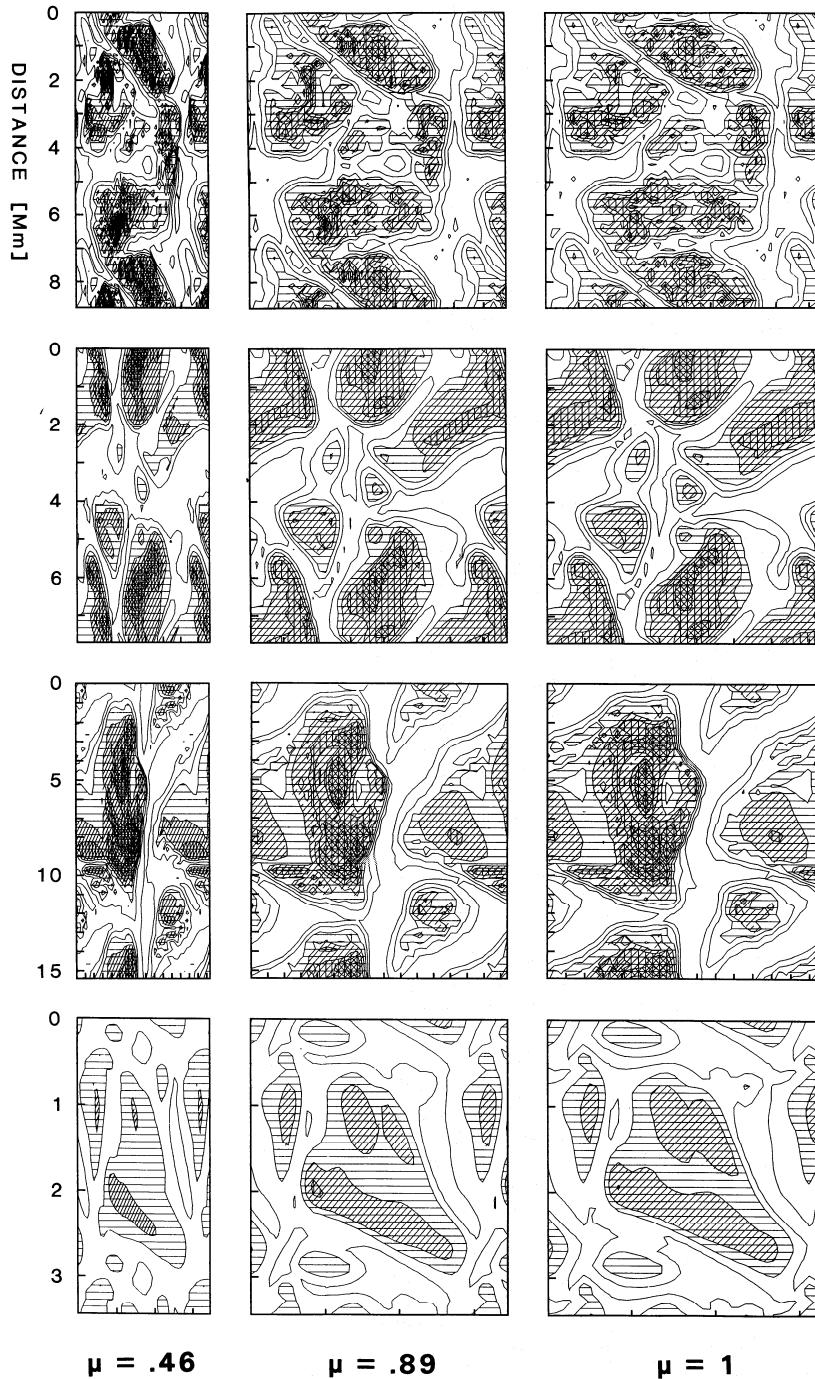
# Granulation on stars

Synthetic images  
[negative] of  
granulation in four  
stellar models

From top:  
*Procyon* (F5 IV-V),  
*Alpha Cen A* (G2 V),  
*Beta Hyi* (G2 IV), &  
*Alpha Cen B* (K1 V).

Disk center ( $\mu=1$ ),  
and two positions  
towards the limb.

## CONTINUUM BRIGHTNESS



$\mu = .46$

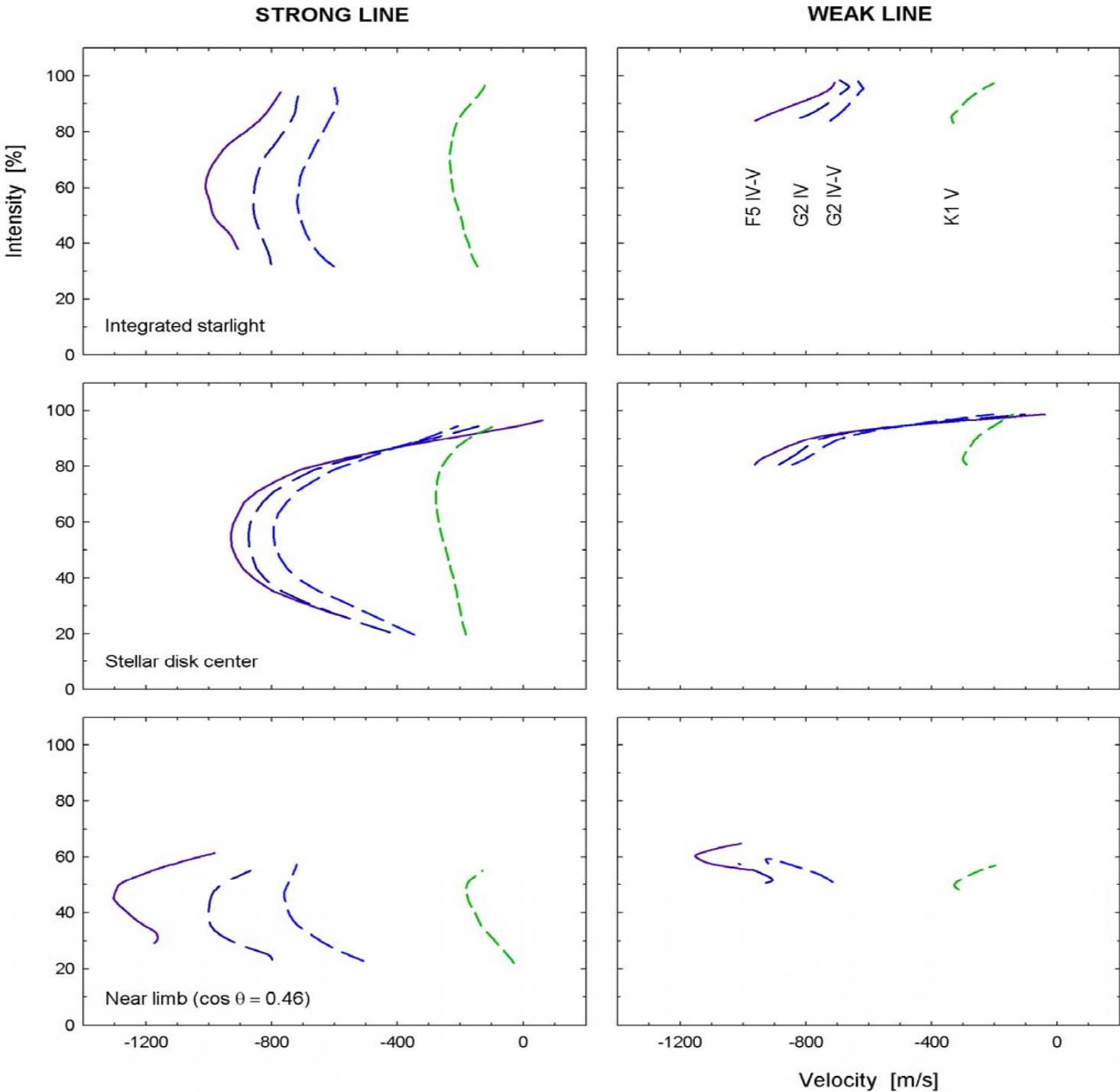
$\mu = .89$

$\mu = 1$

D.Dravins & Å.Nordlund  
Stellar Granulation IV.  
Line Formation in  
Inhomogeneous  
Stellar Photospheres  
A&A 228, 84

# Same spectral line in different stars

Adapted from  
*Dravins & Nordlund,  
A&A 228, 203*



Lineshifts change on  
order 300 m/s  
across stellar disks

# A visible imaging FTS for E-ELT with XAO & integral-field-unit covering a stellar disk ?

• Telescope diameter	42 m
• Interferometer	dual output (with mirror cube corners)
• Interferometer beam diameter	<b>150 mm</b>
• Spectral domain	<b>0.35 – 0.95 μm</b>
• Max spectral resolution	<b><math>2 \cdot 10^5</math> at 0.5 μm</b> ( $d\sigma = 0.1 \text{ cm}^{-1}$ )
• Maximum OPD	<u>6 cm</u> <b><i>could be more ambitious!</i></b>
• Metrologic calibration	<b>1064.4 nm stabilized diode laser</b>
• FOV diameter	<b>2'</b>
• Image sampling	0.03''/pxl (2x2 binning)
• Detectors	two 4Kx4K CCD (15 μm pixel)
• Imaging collimator f/number	2.54

Common fallacy:  
Belief that high optical  
efficiency is crucial to  
scientific discovery

Still ... A grand challenge:  
Design an efficient  
 $R = 1,000,000$   
high-fidelity  
spectrometer for ELTs!

THE  
END